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COMPARISON OF METALLIC vs. MEMBRANE BASED WET ESP TECHNOLOGY FOR PM2.5, SO3 MIST AND MERCURY CONTROL AT A COAL-FIRED POWER PLANT

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Abstract

Several coal-fired utilities have experienced increased SO3 emissions from their existing Wet FGD Scrubbers, especially after installing an SCR for NOx Control. The SO3 goes largely uncollected through the Wet Scrubber appearing as a dense plume at the FGD stack. Sub micron SO3 (H2 SO4 mist) is extremely difficult to remove with conventional technologies, however, Wet Electrostatic Precipitators can readily collect acid aerosol and fine particulate due to greater corona power and virtually no reentrainment. The historical limitations on Wet Precipitators have been their high cost because of stainless steel metal used in their manufacture.

Ohio U/ SEI/CRCAT have developed a new membrane based, Wet ESP with dramatically reduced cost and weight compared to metallic wet ESPs. Cleaning of the corrosion resistant fabric membranes, is facilitated by capilliary action between the fibers, providing even water distribution, & continuous flushing which removes collected material without spraying, so the entire precipitator remains on line.

DOE's National Energy Technology Laboratory has awarded SEI/CRAT and Ohio University a grant to compare metallic and membrane based wet ESP technology in a pilot unit at Penn Power's Bruce Mansfield Plant in Shippingport, Pa. This paper will present the work & results to date.

Introduction

Dry Electrostatic precipitators are very efficient at removing most particulates, with collection efficiencies exceeding 99% on a mass basis. They are durable, cost effective, and easy to operate. However, present dry precipitators are not adequate to address the challenges of fine particulates, particles with aerodynamic diameters less than 2.5 um, known as PM2.5.

Dry electrostatic precipitators exhibit significantly reduced collection efficiencies for particles less than 1.0 um (submicron) in diameter due to inherent charging mechanism limitations on particles in this range, as shown in Figure 1 (Flagan and Seinfeld, 1988). These limits on charging mechanisms for fine particulates are exaggerated in dry precipitators due to low corona power levels caused by the resistivity of the ash layer that accumulates on the collecting surfaces (Altman et al., 2001; Altman et al., 2001a). Further, last field re-entrainment losses - particles that are captured but are then "knocked" back into the gas stream as a result of rapping – can increase emissions of some primary PM2.5. In addition, dry precipitators are virtually incapable of removing fine particles formed by gas-to-particle conversion of nitrates and sulfates (secondary PM2.5) emitted from the combustion process.

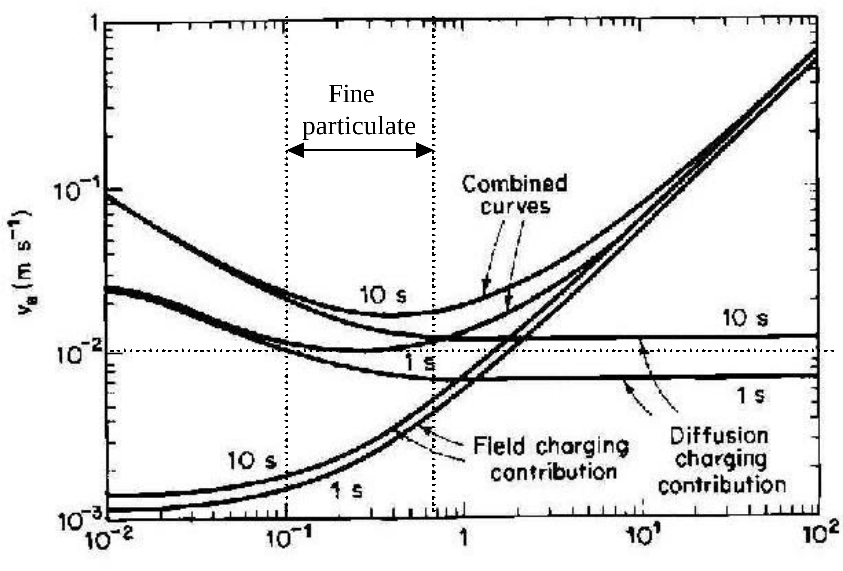


Figure 1. Combined Diffusion and Field Charging Curves (Flagan and Seinfeld, 1988)

Fine particulate is of concern to coal-fired utilities because it effectively scatters light, leading to increased stack opacity. Most states limit opacity at the outlet of the stacks to either 10% or 20%. Without the capability of removing the fine particulate, the most viable option for decreasing opacity is to curtail power output, thus losing revenue from power sales. Soot or condensed hydrocarbons and acid aerosols, are capable of causing significant opacity problems at concentrations as low as 10 ppm (v). Unfortunately, these types of fine particulate are more prevalent to boilers using low NOx burners (compared to standard coal-burners) because of the fuel-rich environment near the burner tip. Acid aerosols form when an acid (notably sulfuric acid) condenses, providing excellent condensation nuclei for water accumulation, eventually creating aerosol particles 1-2 μm in diameter. Sulfuric acid condensation nuclei are prevalent when SO_3 concentrations are high, either because of burning high sulfur coal or when selective catalytic reduction (SCR – used for NOx control) catalyst beds oxidize significant amounts of SO_2 to SO_3. SCR's are increasingly being used in coal-fired power plants for NOx control, especially in the Midwest.

Wet precipitators hold significant promise for control of fine particulates, as well as sticky, or high resistivity particulates. Wet precipitator re-entrainment is virtually nonexistent due to adhesion between the water and collected particulate. Wet precipitators can provide up to several times the typical corona power levels of dry precipitators, greatly enhancing collection of submicron particles (Altman et al., 2001; Altman et al., 2001a). Wet precipitators can also lower the gas stream temperature by convective cooling, promoting condensation, and enhancing the collection of soluble acid aerosols.

Still, there are formidable obstacles to implementing large-scale wet precipitation at coal-fired generation units. A wet environment is corrosive, especially when the liquid reacts with acid gas, rapidly deteriorating the precipitator's collection surfaces (Masuda, 1977). Combating this corrosive potential requires use of very expensive materials, usually high-alloy stainless steels. Large particulate loading in untreated flue gas is also problematic. Corona current suppression, due to low mobility of charged particles in the inter-electrode region, can overwhelm the positive effects of low collector resistivity (Altman et al., 2001; Altman et al., 2001a).

Other obstacles include disruption of the electric field when spraying to remove the collected particulate.

A new type of wet/saturated electrostatic precipitator has been developed by researchers at Ohio University & Southern Environmental, in which fabric membranes replace traditional metal collecting electrodes. Tests indicate that membranes made from materials that transport liquid (primarily water) by capillary action are effective collection electrodes. The membrane collecting electrodes may consist of a number of different types of fiber-based fabrics, such as those made from carbon, polypropylene, Ryton, Teflon, or other materials that support capillary (internal) and sheeting (external) flow of water. Capillary flow promotes well-distributed water flow both vertically and horizontally. Well-distributed water transport, in both internal and external (sheeting) flow, is necessary for particle collection, removal and transport.

SEI has prior utility wet precipitator experience, having built a novel wet precipitator to control sub-micron particulate from coal flue gas at the Sherburne County Generating Plant (Sherco Station) located in Becker, Minnesota (Henningsgaard, et al., 1995). Before installing the wet precipitators, Sherco Station controlled SO_2 and particulate emissions using down-flow, venturi-throat scrubbers. While successfully controlling the large particulate and SO_2 gas, the wet scrubbers were inadequate in controlling fine particulate, resulting in opacity as high as 42%. After pilot testing, SEI built a module to handle 250,000 acfm of flue gas that achieved an emissions rate less than 0.01 lbs/Mbtu, effectively reducing opacity to below required levels.

Discussion

Problems with existing wet electrostatic precipitators

In most wet precipitators, both tubular and flat-plate, the collection surface normally has the form of a plain, *solid*, *continuous* sheet of metal or plastic. Therefore, the flushing liquid (water) passing over the surface tends to "bead" due to both surface tension effects as well as the initial geometric surface imperfections ("hills and valleys") of the surface. Because the flushing liquid cannot be uniformly distributed over the surface, this beading can lead to channeling and formation of "dry spots" of collected particles. The resulting build-up of collected material can cause the electrical performance of the precipitator to degrade because the accumulated material is not as good a conductor as the underlying substrate or the water. As a result, current flow is inhibited, potentially leading to large-scale back corona, which results in increased emissions from that section of the electrostatic precipitator.

Most "old-design" wet precipitators employ atomization or spraying to more uniformly distribute liquid over the surface. Increasing the number of droplets and decreasing their respective size can minimize beading, and thus reduce the number of dry spots. However, any spraying onto the surface will inevitably produce a misting effect in the gas channel. This aqueous mist is much more conductive than the typical gas that is moving through the gas passages. As a result, the high voltage electric field, which is used to both charge the particles and drive them to the collecting plates, will have a conductive path to ground, shorting out the field. To avoid this grounding, called sparkover, the field voltage is usually reduced or switched off during spraying.

Metal plate wet precipitators also face problems of corrosion, so the internals must be made of expensive alloys.

New Membrane Wet Electrostatic Precipitator Design

The new membrane design replaces the traditional collecting electrodes made from solid sheets/tubes, with fabric membranes made from materials capable of dispersing the cleaning liquid by capillary action. Materials such as woven or non-woven fabrics, can be used as collecting electrodes. The capillary action of the membrane material provides uniform distribution of water in both vertical *and horizontal* directions until the saturation point is reached. Once the membrane becomes saturated, a thin layer of water begins to flow downward over the surface of the membrane, flushing the surface of collected particles.

The wetting action of the flushing liquid enables the collected particulate to be evenly and continuously flushed from the collecting electrode. This solves a major historical problem in wet electrostatic precipitators, both of the wet upflow and wet horizontal flow types, which is to keep the collecting electrodes continuosly clean.

The flushing liquid can be delivered to the membrane in a number of ways. The most important design aspect is that the water is "dripped", not sprayed, over the collecting surface (Figures 2 & 3). *Capillary action* of the membrane material, along with an assist from gravity, delivers the water throughout the membrane eliminating splashing or spraying. A controlled amount of water can be delivered *through* the membrane's upper edge. This may be accomplished via a pressurized header, or other similar device, mounted at the upper end of the membrane. The amount of water delivered and the resulting thickness of the surface liquid film (after membrane saturation is reached) can be controlled. Tests indicate that adequate flushing of collected material can be achieved with only 1.5 – 2.5 gallons-per-minute per 1,000 ACFM of saturated gas.

Figure 2. **Facility for Surface Flow Studies**

Figure 3. **Top view of Water Distribution Test Stand**

Advantages of the New Membrane Precipitator

Because the liquid film is also the collecting surface (i.e. it conducts electricity), the membranes can be made from corrosion resistant, nonconductive materials like polypropylene, Ryton, or reinforced plastics. Utilization of these materials minimizes problems of corrosion, while offering a much lower cost alternative to stainless steels and expensive alloys.

In addition, the cost of installation and transportation may be significantly lower because the weight reduction may be as much as a 60-80% compared to steels.

Unlike solid substrates that form "dry spots", these two well distributed and combined flows, capillary and surface, also service as a shield, which at least partially protects the membrane over its entire surface against abrasion by particles, and will also dilute various chemicals.

The membrane collecting electrode can be kept very flat with a small amount of tension.

With the virtual elimination of splashing by this new water delivering system (through the membrane) and water distribution system (mostly through wicking) a continuous flow of water can be maintained while the electric field is not interrupted.

Another benefit of the fabric membrane, over a metallic or solid collecting plate, is the significantly reduced quantity of water or flushing liquid required to keep the membrane clean. In the case of the wet (saturated) upflow design, we can compare the new membrane technology to the Northern States Power (NSP) installation, which utilizes metallic 304 Stainless Steel Collecting Plates in a two-field arrangement (Henningsgaard et al. 1997). The water consumption at NSP amounts to approximately 5 GPM per KACFM. By comparison also to the hybrid design, such as the unit previously operating at Mirant's Dickerson Station, that metal plate design requires 6 times more water for flushing than the membrane design. Water consumption will be a critical operating cost variable and minimizing the required water usage is an advantage for the membrane technology.

Experimental Results

The following section describes the four facilities used to conduct the tests, followed by the most important results.

Pilot Testing I

After the laboratory tests at Ohio University, it was decided to build a pilot unit at SEI. This pilot unit would be a more realistic size with some components installed at "full size."

The pilot unit was designed to answer the following questions:

Does the water indeed "sheet" down the plate as we expect or does it channel?

Will the dust build up on "dry spots" and cause channeling?

Is it easy to keep the fabric memb ranes in alignment and keep them clean?

Does the Elex RDE discharge electrode work well in this arrangement?

Can the wet fabric membrane handle higher inlet dust loads?

What type of fabric is optimum for the wet unit, a lighter material or heavier fabric?

Can the spray system be made much simpler than in a conventional wet ESP?

Will the water sheeting effect achieve the performance of a "condensing" wet ESP?

The vertical test section, held the discharge electrodes and collecting membranes The cross section of the unit was an 18-by-25 inch box. The schematic of the top view is given in Figure 6 and photographs are shown in Figure 7 & 8. There were three collecting membranes inside the box, each 16 inches wide. Two discharge electrodes were located in between the three membranes, providing two vertical gas passages for the gas/dust to flow between the membranes (from bottom to top). The discharge electrodes were spaced 5.75 inches from the collecting surfaces. Both were centered in the 18 inch side of the box, supported by a high voltage frame located above the collecting membranes. The membranes were supported at the top and bottom loops by 1-by-2 inch rectangular steel tubing. Fourteen 1/8-inch holes were drilled in the bottom of the top tubing to distribute the water to the membranes' upper edge through the bottom of the membrane loop.

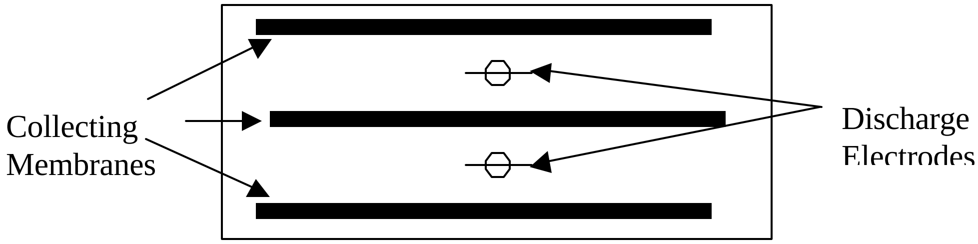


Figure 6. Pilot wet precipitator configuration

Heaters were used to bring the inlet air temperature to 150-250°F. The primary air fan used in the pilot unit was capable of deliveries up to 1,700 acfm. A vibrating screw feeder was used to deliver the ash to the precipitator. The saturation sprays were used to partially saturate the gas stream with water prior to entering the Wet ESP section. Figure 8 shows the inlet section components of the pilot precipitator.

Figure 7: Overall Pilot Unit.

Figure 8: Inlet section of precipitator

Results of Pilot Unit

Preliminary testing was performed to examine electric field behavior with water flow over the non-conducting membrane substrate. The transformer rectifier voltage was increased until high sparking inhibited operation, establishing the maximum voltage. Figure 9 shows V-I-curve for the pilot precipitator using the wet membrane collection for air only (no particulate) with the Power Plus transformer-rectifier set provided by NWL. This figure illustrates the precipitator using water flowing through non-conducting membranes had power profiles consistent with the behavior of conventional wet precipitators (Jassund and Roberts, 2000).

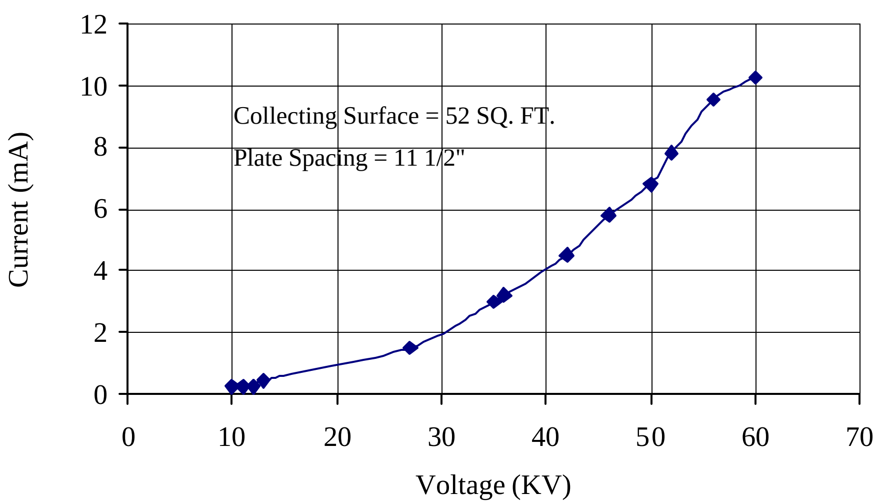


Figure 9. V-I curve for the pilot wet precipitator using wet membrane collectors

Test runs were performed to visualize the pilot's ability to remove particulates. Pictures were taken before energizing the field and a few seconds after the field was energized. The dust loading, temperature, and flow conditions were kept constant between the two displayed images of Figure 10, providing an indication of the effectiveness of the wetted collection membranes.

Figure 10. Dirty and clean stacks (two seconds after energizing field)

Corrosion Resistance

The other important problem addressed by membrane use is the historical high cost of corrosion resistant alloys in wet precipitator applications. These alloys include 316 stainless steel, Hastelloys, and other nickel-based alloys. By comparison, fabric membrane material is significantly less expensive and in many cases more corrosion resistant than metals.

To test how various membrane materials behave in highly corrosive environments at elevated temperatures, a closed loop testing system was constructed as schematically shown in Figure 11. The system is designed for long-term, continuous operation without interruption. The system produces hot water for elevated temperature (80°C) testing of nine separate chemical solutions-fabric combinations.

The nine tanks contain combinations of the materials Ryton, polypropylene and teflon in solutions of acids and bases. Specifically, the solutions are titled:

"Sulfuric Acid"	H_2SO_4 and H_2O to pH of 1.5;
"Ammonia"	1500 ppm NH_4Cl, 1% $(NH_4)_2SO_4$ in distilled water
"Corrosive"	800 ppm HF, 30000 ppm HNO_3, 60000 ppm H_2SO_4, 8000 ppm HCl in distilled water.

The materials were sampled and tested for Mullen Burst strength.

The Mullen Burst strength results are shown in Figure 12 as a function of time.

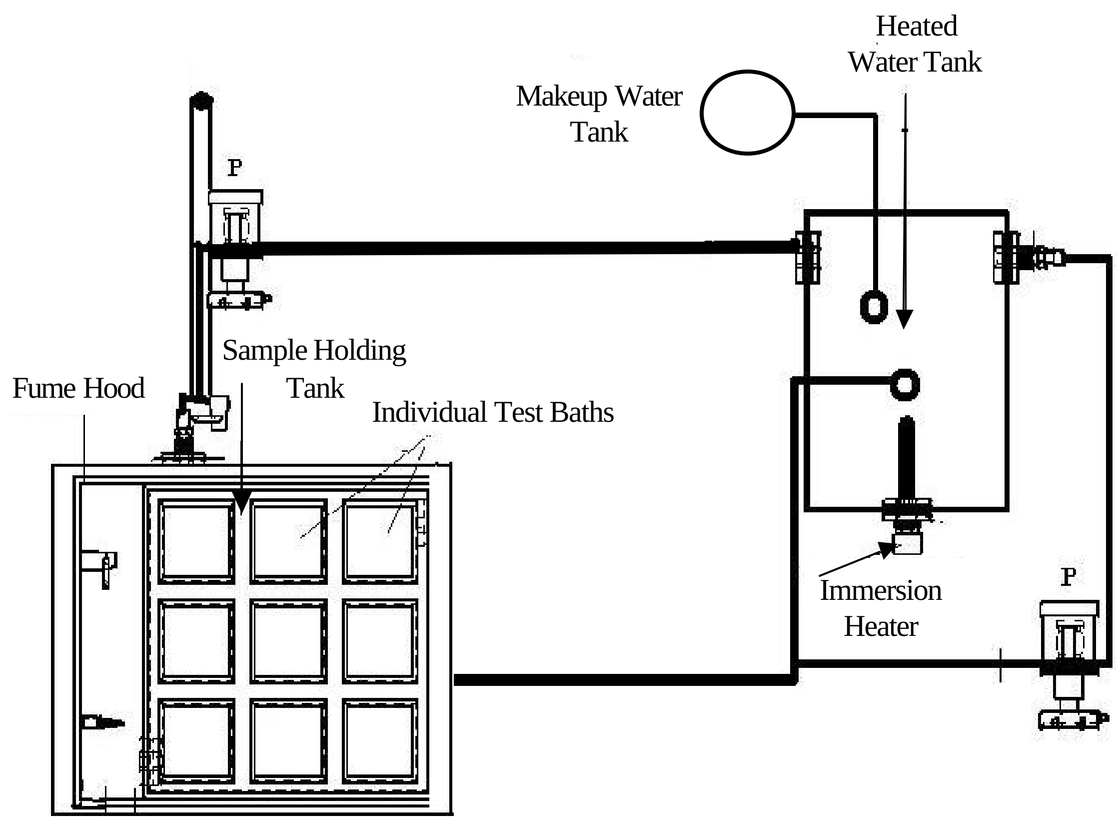
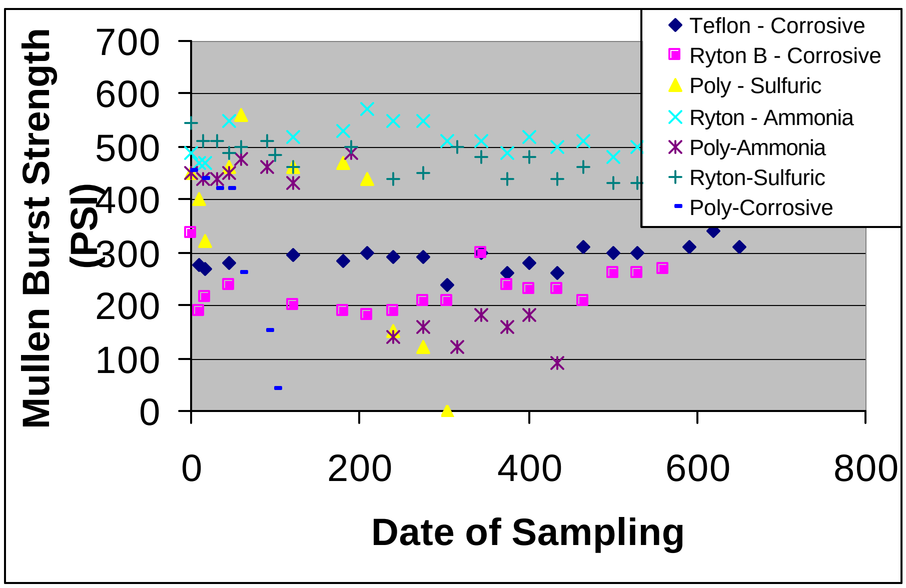


Figure 11. Accelerated Chemical Corrosion Testing Apparatus

Figure 12. Accelerated chemical corrosion strength testing results



Potential Applications of Membrane Wet Precipitation

The main applications envisioned for the membrane WESP are to collect fine particulate, and acid aerosols, after scrubbers:

- After FGD scrubbers in the Utility Industry.
- After upstream particulate scrubbers in industrial applications.

For these applications, the membrane wet precipitator technology has several significant advantages over existing technologies as discussed below.

Advantages of a Wet Membrane Up-Flow Unit

Generally with "typical" wet, upflow units such as the one at NSP, and with horizontal-flow wet units, the ESP must be designed with an "extra" field which can be out of service during cleaning, substantially increasing the cost of the wet unit. Because the membranes can be continuously flushed, the possibility exists to design the unit with a single field and still collect fine particulate and SO_3 mist. Obviously this will significantly reduce the costs compared to existing technology. (Note this does not consider that space-charge effects might inhibit a single-field unit, should the concentration of acid aerosols be extreme.)

Savings with the membrane technology could be substantial compared with the cost of the traditional stainless steels and especially with corrosion resistant alloys, such as Hastelloy. Recent papers (S.Bjorkluns et al. 2003) have projected the costs of metal plate WESP's as:

- $30-40/kw for a 3 field vertical-flow metal plate design.
- $60-$90/kw for a horizontal flow metal plate design.

We project that a 2-field, upflow, membrane WESP, located on top of an existing Wet FGD scrubber will cost less than $25/KW on an installed basis.

Further, the weight of the collecting electrodes can be reduced by as much as 75%, making it easier to install the membrane curtains in existing up-flow scrubbing towers.

Additionally, there is strong evidence that the membrane curtain can handle higher inlet dust loadings since it can be flushed continuously. In the case of an "NSP design" this would allow the upstream scrubber to operate at a lower pressure drop, saving power and reducing operating cost. A 5" SPWG (ΔP) savings on 1,000,000 acfm of airflow is worth approximately $250,000 per year (Henningsgaard et. Al. 1997).

DOE Pilot Project

An 18-month program is being conducted to demonstrate the use of wet membrane collecting surfaces for collection of acid aerosols, fine particulate, and soluble oxidized mercury, at First Energy's Bruce Mansfield Station in Shippingport, PA. This pilot plant is designed to: 1) compare the collection capabilities of fine particulate by membranes in a wet precipitator to the collection capabilities of steel plates, 2) measure key material properties regarding sustainability during pilot operation, 3) quantify the collection of soluble mercury species on membrane collecting surfaces. The objective of this work is to demonstrate, in actual plant conditions, that membrane collecting surfaces in wet precipitators can collect fine particulate, acid aerosols and soluble Hg species more efficiently due to higher specific power, superior corrosion resistance, and better wetting and cleaning qualities compared to metal collecting electrodes in a wet precipitator.

The feasibility of both project completion and success are extremely high. The steel plate wet precipitator pilot unit already in operation at the Mansfield Station shows significant reduction of fine particulate as evidenced by much lower apparent opacity. Because of bench-scale and smaller–scale pilot testing, there is significant confidence that the membrane substrates will further improve capabilities of the precipitator.

Conclusions and Recommendations

Membrane technology offers significant and measurable improvement over existing Wet ESP technology in saturated wet upflow precipitators. There is the distinct possibility, not only for better performance on acid aerosols and PM 2.5, but also, to achieve lower costs compared to alternative technologies.

Continuing tests will help refine the capability and lower cost of this improvement in WESP technology.

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